Possible emplacement of crustal rocks into the forearc mantle of the Cascadia Subduction Zone

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[1] Seismic reflection profiles shot across the Cascadia forearc show that a 5–15 km thick band of reflections, previously interpreted as a lower crustal shear zone above the subducting Juan de Fuca plate, extends into the upper mantle of the North American plate, reaching depths of at least 50 km. In the extreme western corner of the mantle wedge, these reflectors occur in rocks with P wave velocities of $6750-7000$ ms^{-1}. Elsewhere, the forearc mantle, which is probably partially serpentinized, exhibits velocities of approximately 7500 ms^{-1}. The rocks with velocities of $6750-7000$ ms^{-1} are anomalous with respect to the surrounding mantle, and may represent either: (1) locally high mantle serpentinization, (2) oceanic crust trapped by backstepping of the subduction zone, or (3) rocks from the lower continental crust that have been transported into the uppermost mantle by subduction erosion. The association of subparallel seismic reflectors with these anomalously low velocities favours the tectonic emplacement of crustal rocks. INDEX TERMS: 0905 Exploration Geophysics: Continental structures (8109, 8110); 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8180 Tectonophysics: Tomography. Citation: Calvert, A. J., M. A. Fisher, K. Ramachandran, and A. M. Tréhu, Possible emplacement of crustal rocks into the forearc mantle of the Cascadia Subduction Zone, Geophys. Res. Lett., 30(23), 2196, doi:10.1029/2003GL018541, 2003.

1. Introduction

[2] Deep seismic reflections were first observed above the subducting Juan de Fuca plate by a Vibroseis survey acquired across Vancouver Island in 1984 [Yorath et al., 1985]. The reflectors beneath Vancouver Island occur in a 5–8 km thick zone that dips landward and increases in depth from 20 km to 33 km. Referred to as the E reflections, they were interpreted to arise from imbricated mafic and sedimentary rocks [Green et al., 1986] or sedimentary rocks accreted to the base of an underplated mafic unit [Clowes et al., 1987a]. A marine survey shot

off the west coast of Vancouver Island in 1985 [Clowes et al., 1987b] showed that the high-amplitude E reflectors truncate at depth a terrane-bounding fault in the overlying crust, leading to the suggestion that the E reflections represent a regionally extensive shear zone developed in the crust above the subducting plate [Calvert and Clowes, 1990]. A subsequent integrated interpretation of the 1985 data and another offshore survey shot in 1989 showed that beneath the continental shelf the deepest E reflections merge into other reflections that originate at, or just above, the top of the subducting Juan de Fuca plate [Calvert, 1996]. Beneath Vancouver Island the E reflectors may be associated with the presence of fluid-filled porosity of approximately 2%, because a magnetotelluric survey identified a landward-dipping conductivity anomaly at depths similar to the E reflectors [Kurtz et al., 1986].

[3] In 1998, the SHIPS (Seismic Hazards Investigation in Puget Sound) program acquired seismic reflection data through the Strait of Juan de Fuca and Puget Sound with the objective of delineating the crustal architecture to provide constraints on earthquake hazard analyses [Fisher et al., 1999]. In this paper, we present seismic data from this survey that permit the mapping at depth of the E reflectors east of Vancouver Island. We show that the E reflectors reach depths of at least 50 km, and by correlating reflections with a 3-D P wave velocity model, we show that the E reflectors may lie within crustal rocks forced down into the corner of the forearc mantle wedge.

2. Tectonic Setting

[4] In the Early Eocene, the latest stage of subduction began along the margin of the Pacific Northwest [Engebretson et al., 1985]. During this period, two terranes were accreted to the western margin of the continent: the Pacific Rim terrane comprising mainly Mesozoic sediments and metasediments was thrust beneath the Wrangellia terrane that at that time formed the edge of the continent; the predominantly volcanic Crescent terrane was also thrust beneath the Pacific Rim terrane (Figure 1). Rocks of the Pacific Rim terrane do not crop out south of Vancouver
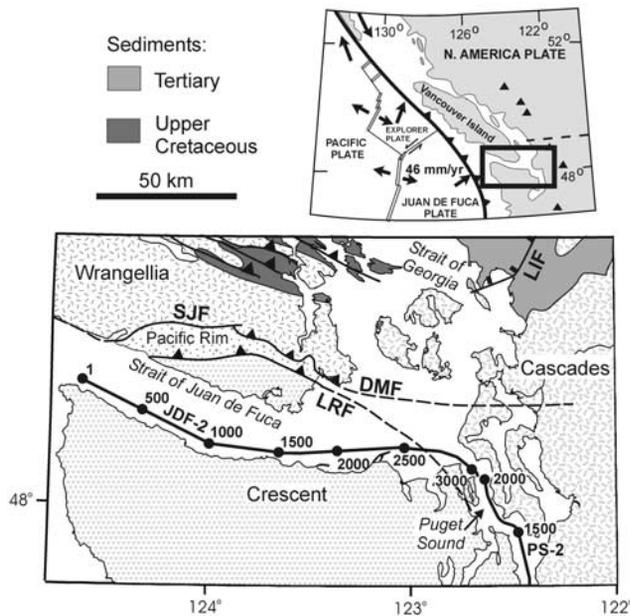
Figure 1. Location of SHIPS seismic reflection profile JDF-2 and the section of PS-2, superimposed on the bedrock geology of southern Vancouver Island and northwest Washington State. Dots indicate every hundredth shot point along the seismic lines. The position of the survey area with respect to the Cascadia convergent margin is shown by the black rectangle in the inset location map. SJF - San Juan fault, LRF - Leech River fault, DMF - Devil's Mountain fault, LIF - Lummi Island fault.

Island, but the Crescent terrane is exposed as far south as Oregon, where it is known as the Siletz terrane.

3.   SHIPS Deep Reflection Data

[5] We show here a composite seismic section that comprises reflection line JDF-2 and part of line PS-2, constructed from data collected during the SHIPS survey (Figure 2). The source for both lines was a 13-airgun array with a total volume of 79-l (4838 in^3), and data were recorded by a 96-channel hydrophone streamer with a 25-m group interval and 2575-m far offset. The average 50-m shot point (SP) interval yielded a nominal 24-fold stacked reflection section.

[6] In the eastern Strait of Juan de Fuca, high levels of coherent noise due to out-of-plane scattering near the seafloor are present in the seismic data. Although most of this noise was removed during processing, which included dip moveout correction and dip filtering, some coherent noise is still present in the displayed section (Figure 2a). The stacked section was migrated and converted to depth using smoothed interval velocities extracted from a 3-D velocity model derived from both SHIPS wide-angle data and local-earthquake first arrivals [*Ramachandran*, 2001]. The seismic reflection data are superimposed on the velocity section (Figure 2b), which extends downward in depth only as far as the deepest cell of the velocity model that has a non-zero ray density. Checkerboard tests indicate that in the eastern part of the Strait of Juan de Fuca, the edges of

structures with a horizontal dimension of 40 km are resolved at depths as large as 30 km [*Ramachandran*, 2001].

4.   Interpretation

[7] We limit ourselves here to the interpretation of the primary feature of the profiles, namely the thick band of high amplitude reflections below 15 km, which is the eastward continuation of the E reflections observed by earlier reflection surveys [*Green et al.*, 1986; *Calvert and Clowes*, 1990].

[8] In the western part of the section, the band of E reflections is 12–15 km thick, and dips approximately 4° to the east. Near shot point (SP) 1500, the apparent dip increases to 15°, and the deepest reflections can be traced eastward and downward to a depth of 50 km, which corresponds to the maximum recording time of the reflection survey. At the southeast end of the section, the E reflections appear subhorizontal due to the orientation of line PS-2, and are approximately 12 km thick. Between SP 2800 on line JDF-2 and SP 1800 on line PS-2, the upper part of the E reflections is indistinct. It is not clear if this change represents the subsurface, or is simply a consequence of reduced data quality.

[9] The position of the top of the subducting Juan de Fuca plate is difficult to identify in both the reflection section and the velocity model. The 7000 ms^{-1} isovelocity contour of the velocity model is subparallel to the E reflections between SP 500 and 2700, deepening from 30 km near the western part of the Strait of Juan de Fuca to approximately 50 km at SP 2850. This geometry is due to the eastward deepening of the subducting slab. If the top of the subducting igneous oceanic crust lay within the E reflections, it would be characterized by P wave velocities of 6500 ms^{-1} to 6800 ms^{-1}. Theoretical calculations of P wave velocity based on mineralogy, temperature and pressure predict a value of 7000 m s^{-1} for the oceanic crust in the Cascadia subduction zone at more than 35 km depth [*Hacker et al.*, 2003], implying that the top of the igneous crust lies beneath the E reflections. Modelling of wide-angle reflections from the oceanic Moho of the subducting Juan de Fuca plate using three different approaches yields estimates consistent with this interpretation [*Tréhu et al.*, 2002; *Graindorge et al.*, 2003; *Preston et al.*, 2003]. Thus we propose that at depths of 30 to 40 km the 7000 ms^{-1} isovelocity contour is a good proxy for the top of the oceanic crust, with an uncertainty of ±3 km. This isovelocity contour is at a similar depth to sporadic reflectors found beneath the E reflectors [*Calvert and Clowes*, 1990]. Our interpreted position of the top of the igneous oceanic crust of the Juan de Fuca plate is marked by the yellow line in Figure 2b, which becomes subhorizontal as the orientation of the seismic profiles change.

[10] The exact cause of the E reflections remains subject to debate, but the seismic sections presented here provide important new constraints. Velocities as high as 6800 ms^{-1} occur at 9–18 km depth as far east as SP 2700. This location corresponds to the eastward limit of the Crescent terrane immediately below the near-surface sediments (Figure 1). Similar velocities in the mid and lower crust above the E reflectors may also represent Crescent rocks. Between SP 500 and SP 3000, the E reflectors are characterized by P wave velocities of 6500 ms^{-1} to 6800 ms^{-1}; these velocities are
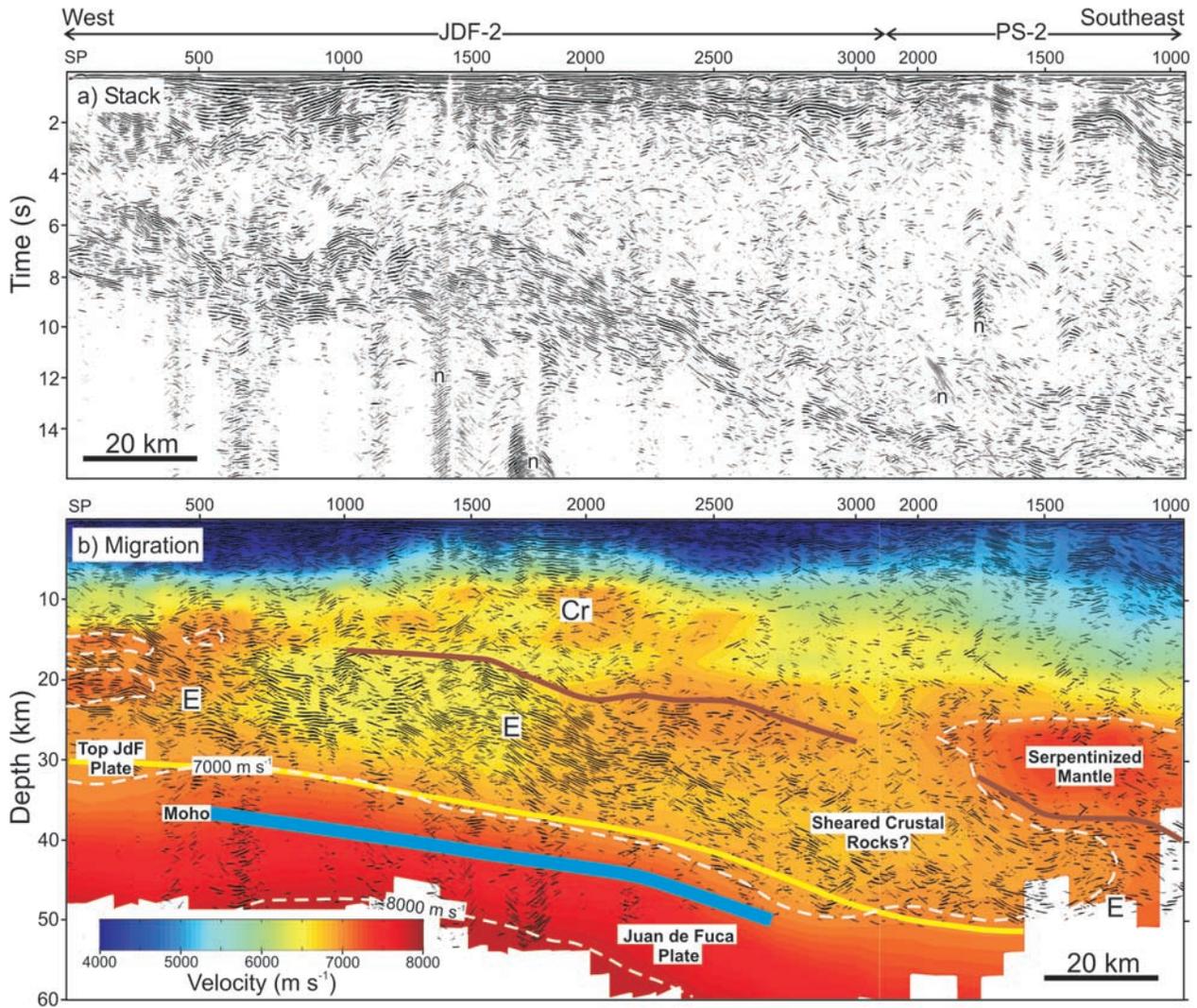
Figure 2. Sections constructed from seismic line JDF-2 and part of line PS-2. (a) Stack. (b) Migration superimposed on interval velocities extracted from the 3-D velocity model. The E reflections dip landward, and continue to at least 50 km depth. A lobe of anomalously low velocity rocks, which is shown by the region above the 7000 ms^{-1} isovelocity contour below 30 km depth, exists in the upper mantle of the forearc, and contains the E reflections. These low velocity rocks may be serpentinized mantle, oceanic crust trapped by backstepping of the subduction zone, or continental rocks that have been transported into the upper mantle by subduction erosion. Cr - Crescent rocks, E - E reflection package, n - most obvious packages of coherent noise. Yellow line - top of subducting plate (±3km), brown line - top of E reflection package, blue line - Moho of subducting plate based on three analyses of wide-angle PmP reflections (line thickness indicates variation between results). The 7000 ms^{-1} and 8000 ms^{-1} isovelocity contours are shown as dashed white lines.

lower than both the overlying Crescent rocks and the underlying oceanic slab. If the E reflections arise from a broad shear zone, then these low velocities might be due to the effects of fracturing or mylonitization. Velocities greater than 7000 ms^{-1} at the western end of line JDF-2, however, suggest that the E reflectors do not always arise in a low velocity zone, and would in this region imply that the E reflectors exist in mafic rocks up to 8 km thick. Lateral velocity variations, as observed within the E reflectors near SP 500, might result from the presence of fluids rising from the dehydrating slab and metamorphism within the crust. Alternatively, shearing, which can generate seismic reflectivity, might have occurred through lithologies with different velocities.

[11] We consider the best interpretation of the integrated velocity and reflection data to be that the E reflections originate from sheared rocks that extend through the lower continental crust and into the forearc mantle above the subducting Juan de Fuca plate. In contrast to earlier studies that have viewed the E reflectors as primarily subducting sediments [*Green et al.*, 1986] or a (possibly sheared) sedimentary underplate to the forearc crust [*Clowes et al.*, 1987a; *Calvert and Clowes*, 1990], our seismic data show that the E reflectors also exist in mafic lithologies and that they are a fundamental structural feature of the forearc mantle linked to presentday subduction because they lie immediately above the subducting slab at depth.

[12]   The E reflectors coincide with unusually low P wave velocities in the extreme corner of the mantle wedge. At the southeast end of the seismic section, velocities increase sharply to 7500 ms^{-1} at 30 km depth. Tomography studies across Puget Sound show this to be the base of the continental crust [*Symons et al.*, 1997; *Stanley et al.*, 1999]. The downdip continuation of the E reflections to 50 km depth is associated with a large lobe with velocities of 6750–7000 ms^{-1}; this lobe is the region above the 7000 m s^{-1} isovelocity contour from 30–50 km depth (Figure 2b). These velocities are anomalously low compared with values of 7500 ms^{-1} at similar depths to the southeast. Velocities of 7500 ms^{-1} are characteristic of forearc mantle, and can be attributed to serpentinization of mantle peridotites [*Zhao et al.*, 2001; *Bostock et al.*, 2002; *Brocher et al.*, 2003].

[13]   We suggest three possible explanations for velocities as low as 6750 ms^{-1} within the low velocity lobe:

[14]   1) High serpentinization of mantle peridotites: It is possible that a shear zone, such as that represented by the E reflections, would trap fluids and facilitate their upward migration. Focussing fluids along the shear zone and into the extreme corner of the mantle wedge could cause locally greater serpentinization, and result in velocities as low as 6750 ms^{-1}.

[15]   2) Tectonic emplacement of subducting oceanic crust into the forearc mantle: If the inter-plate boundary stepped down into the subducting igneous crust, then oceanic crust would be transferred to the overlying continental plate. Such rocks would remain at upper mantle depths, and would exhibit anomalously low velocities, although, as discussed above, velocities lower than 7000 ms^{-1} might not be expected.

[16]   3) Subduction erosion of the lower forearc crust: Continental rocks, perhaps including accreted sediments from the wedge, could be subducted into the upper mantle [*von Huene and Scholl*, 1991] by movement along a shear zone within the continental lithosphere, e.g., the upper part of the E reflectors. However, the P wave velocities of 6750–7000 ms^{-1} observed at 30–50 km depth do not place explicit constraints on the lithologies present because both metasediments and some metabasalts can exhibit such values [*Salisbury and Iullucci*, 2003].

[17]   Although we are presently unable to distinguish clearly between these three possible interpretations, we view a crustal origin of the low velocity lobe as somewhat more likely, because the association of the low velocities with reflectors that have been interpreted as a shear zone suggests some form of tectonic involvement.

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